Current and Future Role of Ultrasonography in the Cardiac Intensive Care Unit

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KEYWORDS

• Ultrasound • Echocardiography • Doppler • Critical care

KEY POINTS

- Diagnostic ultrasound in the cardiac intensive care unit integrates echocardiography with focused multiorgan ultrasonography.
- Doppler echocardiography-derived hemodynamics can be utilized for clinical monitoring and therapeutic guidance.
- Lung ultrasound provides a simple assessment of pulmonary edema that can guide assessment of volume status and diuretic efficacy.
- Doppler echocardiographic hemodynamic parameters have prognostic value when assessed on admission to the cardiac intensive care unit.

INTRODUCTION

The role of ultrasonography in cardiac critical care has evolved in parallel with the changing demographic trends of contemporary cardiac intensive care units (CICUs). Traditionally, echocardiography has been the principal sonographic modality in the CICU. Echocardiography provides non-invasive, bedside assessment of cardiac anatomy and cardiocirculatory hemodynamics that can guide the management of acute myocardial infarction–related complications that dominated the clinical landscape of historical coronary care units.[1,2] However, over the last decade, the predominant pathology of cardiac critical care patients has evolved into a complex mix of acute and chronic cardiovascular diseases with superimposed non-cardiac pathology.[1,2] This transition in the demographics of cardiac critical illness has expanded the scope of ultrasonography in the CICU. The contemporary practice of ultrasonography in the CICU integrates the principles of echocardiography with multiorgan system ultrasonography

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Crit Care Clin 40 (2024) 15–35
https://doi.org/10.1016/j.ccc.2023.06.001
criticalcare.theclinics.com
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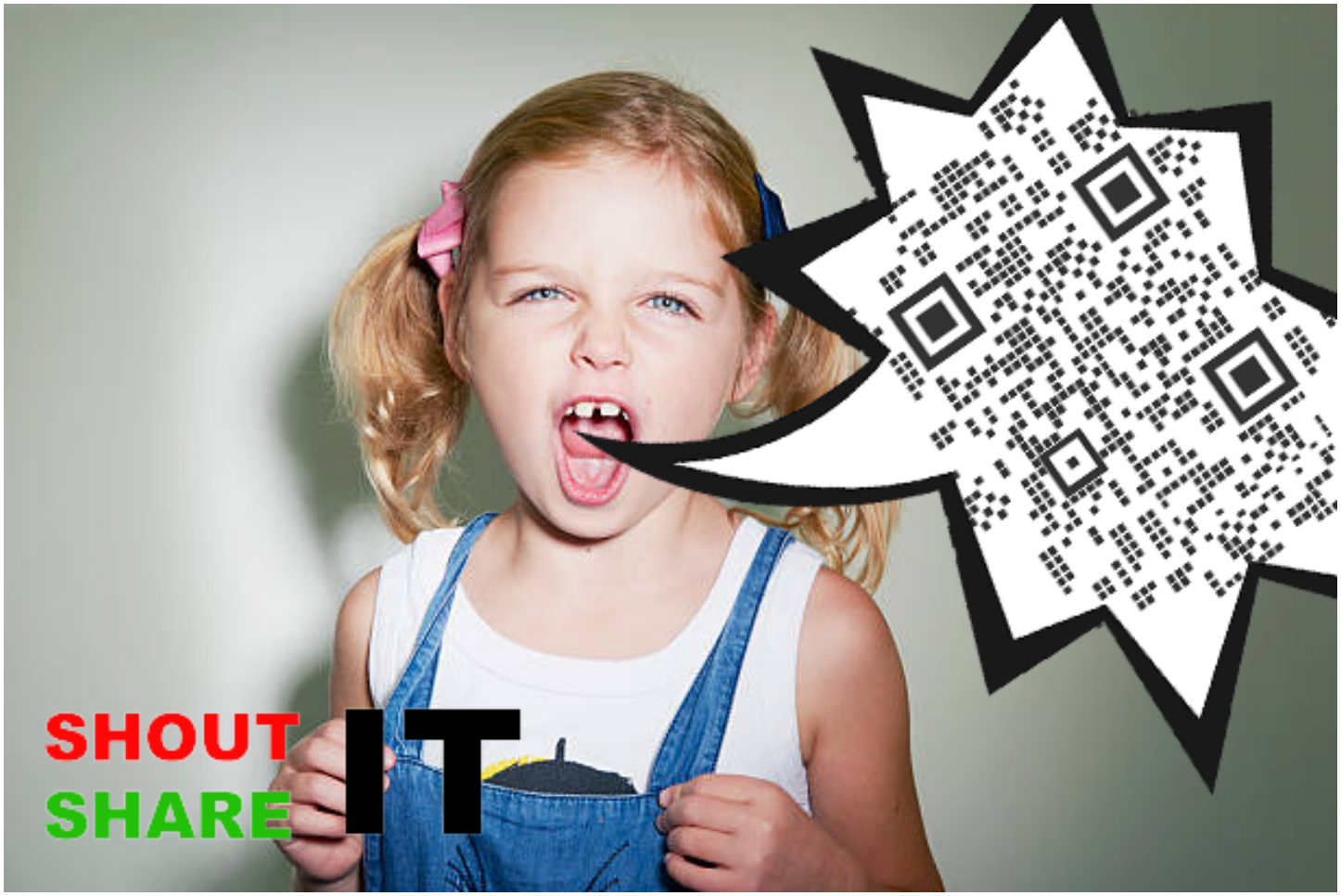
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to create a paradigm of critical care ultrasonography (CCUS). CCUS provides comprehensive anatomic and hemodynamic evaluation for diagnosis, monitoring, therapeutic guidance, and prognosis.

CRITICAL CARE ULTRASOUND – DIAGNOSTIC ASSESSMENT

Diagnostic CCUS is an integrated examination that combines echocardiography and multiorgan system ultrasonography. Echocardiography is the foundation of the examination as it provides a real-time assessment of the cardiac anatomy and cardiocirculatory hemodynamics that are fundamental to understanding respiratory and circulatory failure. Multiorgan system ultrasonography includes a focused pulmonary, abdominal, and vascular assessment (**Fig. 1**), which provides supplemental information that can narrow the differential diagnosis or directly determine the underlying pathophysiology when the findings are interpreted within the scope of the clinical presentation (**Fig. 2**).

Echocardiography

Transthoracic echocardiography (TTE) is universally utilized due to its feasibility, accessibility, and safety. TTE provides rapid assessment of hemodynamically unstable patients and serial monitoring during hospitalization. However, the efficacy of TTE can be limited in the intensive care unit (ICU) where as many as 20% to 30% of patients have suboptimal transthoracic acoustic windows due to patient positioning, body habitus, surgical dressings, devices, or positive pressure ventilation.[3,4] Transesophageal echocardiography (TEE) provides superior visualization of cardiac anatomy and the positioning of the transducer obviates the requirement of adequate transthoracic acoustic windows. In addition, the image resolution of TEE provides excellent 3-dimensional (3D) image rendering, which is invaluable for the evaluation of valvular function, mechanical complications associated with acute myocardial infarction, and surgical planning. However, the accessibility of TEE is limited by the cost of the

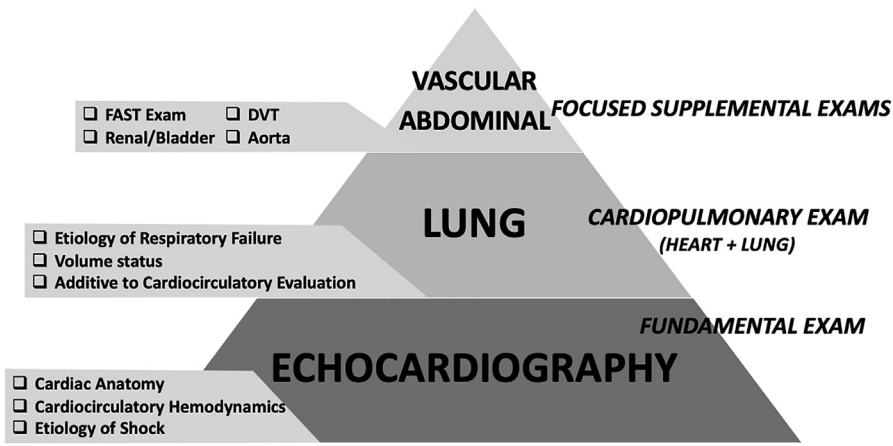

Fig. 1. Critical Care Ultrasound (CCUS). Echocardiography is foundation of CCUS examination as it provides evaluation of cardiocirculatory function. Lung Ultrasound is a core component that combines with echocardiography to create a cardiopulmonary assessment. Focused vascular and abdominal ultrasound are supplemental examinations that are included based on clinical presentation. (*Courtesy of* Brandon M. Wiley, MD; Los Angeles, CA.)

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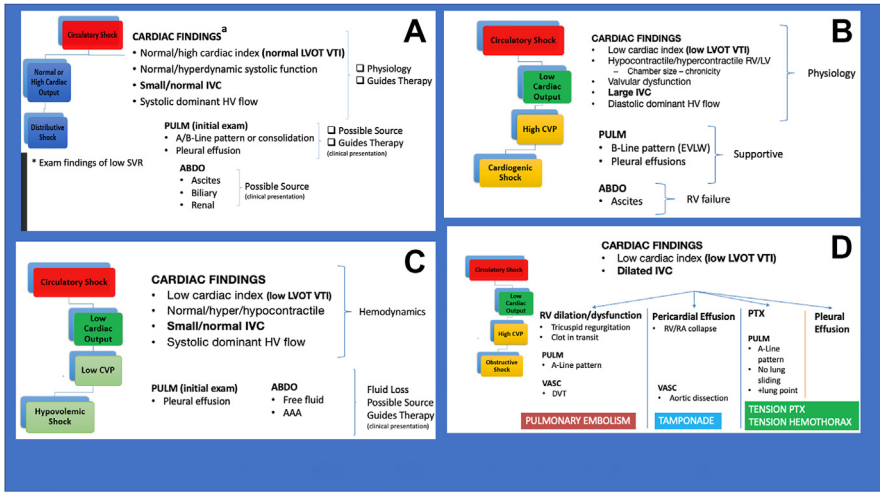

Fig. 2. Diagnosis of shock etiology with critical care ultrasound (CCUS) (*A*) Distributive Shock (*B*), Cardiogenic Shock (*C*), Hypovolemic Shock (*D*), and Obstructive Shock. CCUS utilizes bedside echocardiography to determine cardiocirculatory function through left ventricular outflow tract velocity-time integral (LVOT VTI) assessment of left ventricular (LV) stroke volume and assessment of central venous pressure using inferior vena cava (IVC) size/collapse and hepatic vein flow patterns. Lung, abdominal, and vascular ultrasound provide supplementary information to guide diagnosis and potential therapeutic interventions. DVT, deep vein thrombosis; HV, hepatic vein; IVC, Inferior vena cava; LV, Left ventricle; LVOT, left ventricle outflow tract; PTX, pneumothorax, RA, right atrium, RV, right ventricle, VTI, velocity time integral. (*Courtesy of* Brandon M. Wiley, MD; Los Angeles, CA.)

transducer and the need for cleaning protocols between uses. The need for sedation may complicate the use of TEE, particularly in patients with borderline respiratory or hemodynamic status. Although TEE has been demonstrated to be an exceptionally safe procedure when performed by cardiologists and non-cardiologists, there are risks associated with intubation and probe manipulation.[3,5] Given the potential risks and complexity of TEE, the establishment of more robust clinical training and competency criteria for non-cardiologists and cardiac anesthesiologists is needed for its integration into routine ICU practice.

Two-dimensional (2D) echocardiography is the fundamental modality for cardiac anatomy evaluation and can rapidly identify the presence of cardiac ischemia, mechanical complications, ventricular or valvular dysfunction, intracardiac devices, and pericardial disease. Three-dimensional (3D) echocardiography is an advanced modality that offers enhanced assessment of cardiac anatomy, particularly for structural lesions such as valvular heart disease. Additionally, transthoracic 3D-echocardiography provides an automated assessment of ventricular volumes and systolic function (ejection fraction) that is better than traditional 2D-echocardiography.[6] Color Doppler visualization of blood flow enhances the assessment of valvular function and improves the detection of mechanical complications of myocardial infarction. Spectral Doppler and tissue Doppler imaging (TDI) can provide hemodynamic information analogous to that derived by an invasive pulmonary artery catheter (PAC).[7] The integration of Doppler echocardiography (Doppler echo) principles with 2D-echocardiography affords a visible depiction of the interplay of cardiac anatomy and cardiocirculatory hemodynamics that cannot be matched by pulmonary artery catheterization.

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An important Doppler echo parameter is the calculation of left ventricular (LV) stroke volume (SV). The Doppler echo SV is calculated by multiplying the left ventricular outflow tract velocity-time integral (LVOT VTI) by the cross-sectional surface area of the LVOT. The equation yields the Doppler echo SV in units of milliliters that correlates well with invasive measures of LV SV.[8] The accuracy of the Doppler echo SV depends on the precision of the measurement of the LVOT diameter since this value is squared in the equation for cross-sectional surface area. However, since the LVOT diameter is a constant, dynamic changes in the LVSV can be accurately tracked using only the LVOT VTI, which yields the stroke distance in centimeters.[8] The LVOT VTI provides a high-fidelity evaluation of beat-to-beat forward flow that can be used to assess the hemodynamic response to rapid changes in loading conditions and contractility (**Fig. 3**). Using the normal lower and upper limits of LVOT diameter (1.9–2.3 cm), the LVOT VTI required to generate a stroke volume greater than 65 to 70 mL would be 17 to 23 cm, which correlates well with normal LVOT VTI values (20.5 $\pm$ 4.5 cm).[9–11] Therefore, in hypotensive patients, the LVOT VTI can help define the etiology of shock since values lesser than 14 to 15 cm suggest a high likelihood of low stroke volume and values greater than 22 to 23 cm suggest a high likelihood of normal or elevated stroke volume.[9] (**Fig. 4**) The LVOT VTI can be utilized in the setting of irregular cardiac rhythms by using the average of several cardiac cycles. However, the clinical value of LVOT VTI is diagnostically limited in cases of moderate or greater aortic regurgitation, dynamic LVOT obstruction, or patients with extremely large or small LVOT diameters.

The performance of echocardiography can be augmented with the use of ultrasonic enhancement agents (UEA). These microbubbles, also referred to as ultrasound contrast agents, improve endocardial border delineation for the assessment of biventricular function and the detection of intracardiac thrombi and masses.[12] Additionally, UEAs can be utilized to define the presence of iatrogenic or post-myocardial infarction ventricular pseudoaneurysms[12] (**Fig. 5**). Kurt and colleagues showed that the use of UEAs in the ICU significantly reduced the number of TTE studies that were judged to be uninterpretable (17% to < 1%) or technically difficult (83% to 14%) and positively impacted clinical decision-making.[4] Furthermore, in critically ill patients, utilization of

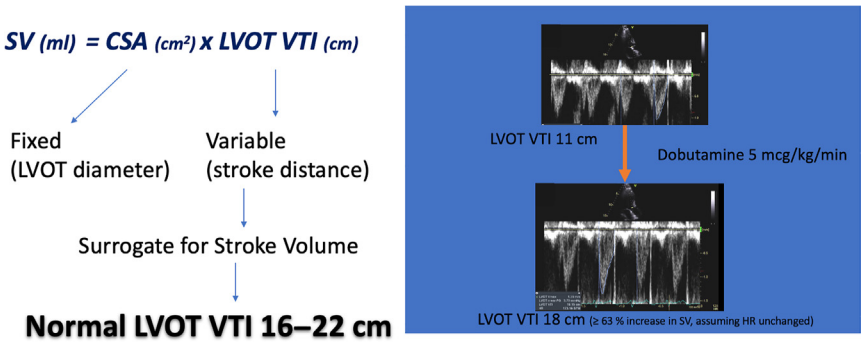
SV (ml) = CSA (cm²) x LVOT VTI (cm)
Fixed
(LVOT diameter)
Variable
(stroke distance)
Surrogate for Stroke Volume
Normal LVOT VTI 16–22 cm
LVOT VTI 11 cm
Dobutamine 5 mcg/kg/min
LVOT VTI 18 cm (≥ 63 % increase in SV, assuming HR unchanged)

Fig. 3. Left Ventricular Outflow Tract Velocity-Time IntegralLVOT VTI The LVOT VTI provides a simplified, high-fidelity evaluation of left ventricular stroke volume. The spectral Doppler tracings demonstrate the improvement in LVOT VTI with the addition of dobutamine in a patient who presented with cardiogenic shock. The improvement of LVOT VTI from 11 cm to 18 cm correlates with a 63% increase in stroke volume. CSA, cross-sectional surface area; LVOT, left ventricle outflow tract; SV, stroke volume; VTI, velocity time integral. (*Courtesy of* Brandon M. Wiley, MD; Los Angeles, CA.)

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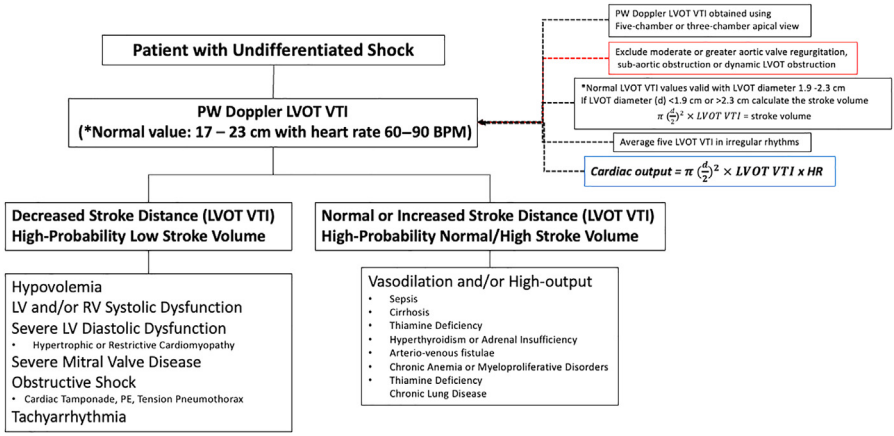
Patient with Undifferentiated Shock
PW Doppler LVOT VTI
(*Normal value: 17 – 23 cm with heart rate 60–90 BPM)
PW Doppler LVOT VTI obtained using
Five-chamber or three-chamber apical view
Exclude moderate or greater aortic valve regurgitation,
sub-aortic obstruction or dynamic LVOT obstruction
*Normal LVOT VTI values valid with LVOT diameter 1.9 -2.3 cm
if LVOT diameter (d) <1.9 cm or >2.3 cm calculate the stroke volume
$\pi\left(\frac{d}{2}\right)^2 \times LVOT\ VTI$ = stroke volume
Average five LVOT VTI in irregular rhythms
Cardiac output = $\pi\left(\frac{d}{2}\right)^2 \times LVOT\ VTI \times HR$
Decreased Stroke Distance (LVOT VTI)
High-Probability Low Stroke Volume
Normal or Increased Stroke Distance (LVOT VTI)
High-Probability Normal/High Stroke Volume
Hypovolemia
LV and/or RV Systolic Dysfunction
Severe LV Diastolic Dysfunction
• Hypertrophic or Restrictive Cardiomyopathy
Severe Mitral Valve Disease
Obstructive Shock
• Cardiac Tamponade, PE, Tension Pneumothorax
Tachyarrhythmia
Vasodilation and/or High-output
• Sepsis
• Cirrhosis
• Thiamine Deficiency
• Hyperthyroidism or Adrenal Insufficiency
• Arterio-venous fistulae
• Chronic Anemia or Myeloproliferative Disorders
• Thiamine Deficiency
Chronic Lung Disease

Fig. 4. Simplified Assessment of Undifferentiated Shock Using Echocardiographic Stroke Distance. The echocardiographic stroke distance refers to the left ventricular outflow tract velocity time integral (LVOT VTI) in units of centimeters. The LVOT VTI is a high-fidelity measurement of systolic forward flow and it can be used in a simplified algorithm to assess the stroke volume in patients presenting with shock. * indicates normal value: 17-23 cm with heart rate 60-90 BPM. BPM, beats per minute; HR, heart rate; LV, left ventricle; LVOT VTI, left ventricle outflow tract velocity time integral; PE, pulmonary embolism; PW, pulse wave; RV, right ventricle. (*Courtesy of* Brandon M. Wiley, MD; Los Angeles, CA and Jose Diaz-Gomez, MD; Houston, TX.)

UEAs was associated with lower in-hospital mortality when compared to propensity-matched patients that underwent non-UEA TTE.[13] The safety of UEAs in critically ill patients has been well documented in large studies.[4,12–14] Although the use of UEA has been shown to be safe in small studies involving extracorporeal membrane

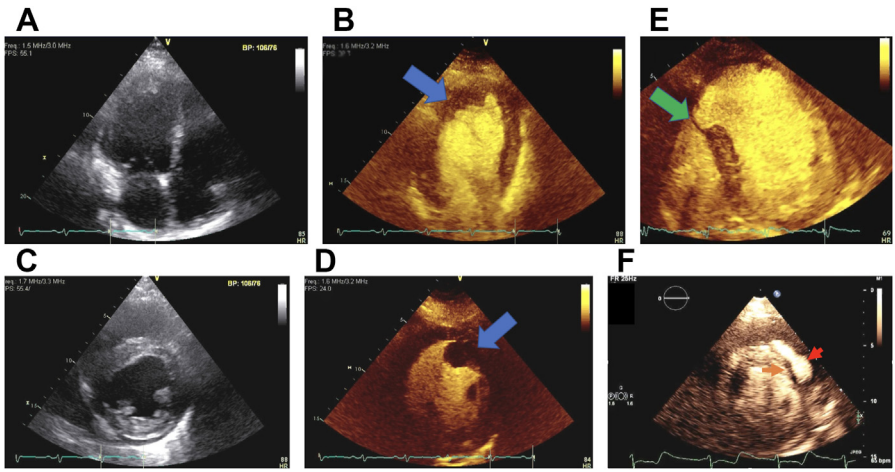

Fig. 5. Ultrasound Enhancement Agent (UEA) for Complications of Acute Myocardial Infarction (*A*, *B*) This patient presented post-myocardial infarction cardiogenic shock. The left ventricle was dilated and ejection fraction was less than 25%. The addition of UEA (*B–D*) demonstrates large thrombus burden (*blue arrows*). (E) Demonstrates post-myocardial infarction ventricular septal defect at the site of the thinned myocardium (*green arrow*). (*F*) Demonstrates active extravasation through ruptured myocardium (*orange arrow*) into a pseudoaneurysm cavity (*red arrow*). (*Courtesy of* Brandon M. Wiley, MD; Los Angeles, CA".)

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oxygenation (ECMO), close monitoring is important since microbubbles can on rare occasion trigger the ECMO bubble detector and cause shutdown of the circuit.[15,16]

Lung Ultrasonography

Lung ultrasonography (LUS) is a fundamental component of CCUS. LUS is a simple, efficient, and highly feasible examination that provides important clinical information regarding both respiratory and cardiocirculatory function. Although the examination can be performed using multiple ultrasound transducers (2–4 MHz phased array, 2–5 MHz curvilinear, or 7.5–12 MHz linear), the use of the phased array transducer allows it to be easily integrated into echocardiography to provide a simultaneous cardiopulmonary ultrasonography examination.[17] The LUS assessment consists of several cardinal sonographic findings of the lung pleura and parenchyma.[18] The pleura appears as a bright, thin horizontal hyperechoic reflector that normally demonstrates respirophasic motion or "lung-sliding" due to movement of the well-apposed parietal and visceral pleural layers. The loss of normal "lung-sliding" suggests either a loss of apposition of the pleural layers due to a pneumothorax or the presence of a primary pulmonary process such as emphysema or acute respiratory syndrome that disrupts normal pleural physiology. Abnormal thickening and irregularity of the sonographic pleural line can suggest the presence of pulmonary fibrosis or underlying pathologic pulmonary process.[19] A pleural effusion is visible as an anechoic space between the pleura layers. The LUS parenchyma assessment depends on the relative aeration of the insonated lung zone. In the setting of normal lung aeration, the LUS demonstrates horizontal reverberation artifacts of the pleural line (A-lines). As the density of the lung increases with corresponding decrease in aeration, vertical hyperechoic ring-down artifacts called B-Lines develop that emanate from pleural line and abolish the A-lines. B-Lines indicate the presence of a sonographic interstitial pattern caused by increased lung density[17–19] (**Fig. 6**). "Wet" B-Lines are caused by cardiogenic or non-cardiogenic extravascular lung water (EVLW) and "dry" B-Lines occur in the setting of interstitial thickening from a primary pulmonary process such as fibrosis. "Wet" B-Lines are dynamic and increase in number with increasing burden of edema and decrease in number with the removal of fluid.[18] The dynamic nature of "wet" B-Lines is clinically valuable and can be used to assess the burden of pulmonary edema and monitor the efficacy of therapeutic interventions.[17,18,20] Additionally, the distribution of B-Lines across the thorax is a key diagnostic feature. The presence of bilateral B-Lines indicates a diffuse interstitial process such as pulmonary edema, whereas unilateral B-Lines suggest a more focal process such as pneumonia.[17–19] The final cardinal finding of LUS is the presence of consolidation, which represents an extreme loss of aeration causing the lung parenchyma to appear with an echodensity similar to a solid organ such as the liver.

LUS imaging protocols utilizing the cardinal findings of lung-sliding, A-Lines, B-Lines, and consolidation and effusion correlate well with computed tomography imaging and provide accurate diagnosis of acute respiratory failure in the ICU.[21,22] Furthermore, LUS is more sensitive than standard chest radiography (CXR) for detecting the presence of EVLW (pulmonary edema).[18,23] Focused LUS imaging protocols have been well-documented to outperform CXR for the diagnosis of symptomatic heart failure in undifferentiated patients in the emergency department.[24,25] The integration of LUS into simplified cardiac ultrasound provides a more efficient and expedited diagnosis of the etiology of undifferentiated dyspnea when compared to standard practice in the emergency room.[26] **Fig. 7** demonstrates a simplified algorithm for the diagnosis of the etiology of respiratory insufficiency using integrated LUS and echocardiography.

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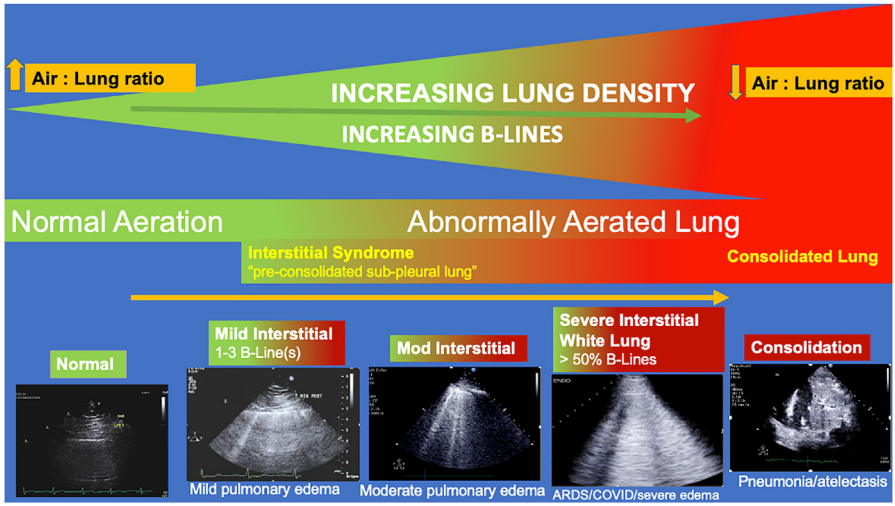

Fig. 6. B-Lines Indicate Increased Lung Density (Decreased Aeration). B-Lines (sonographic interstitial pattern) indicate abnormal lung aeration. The number of B-Lines increases along a spectrum of increasing lung density caused by increasing amount of extravascular lung water. In the setting of severely reduced lung aeration due to acute respiratory distress syndrome or severe pulmonary edema, the B-Lines become confluent and the lung appears white. Consolidated lung has the ultrasound appearance similar to the liver or spleen. (*Courtesy of* Brandon Wiley, MD; Los Angeles, CA.)

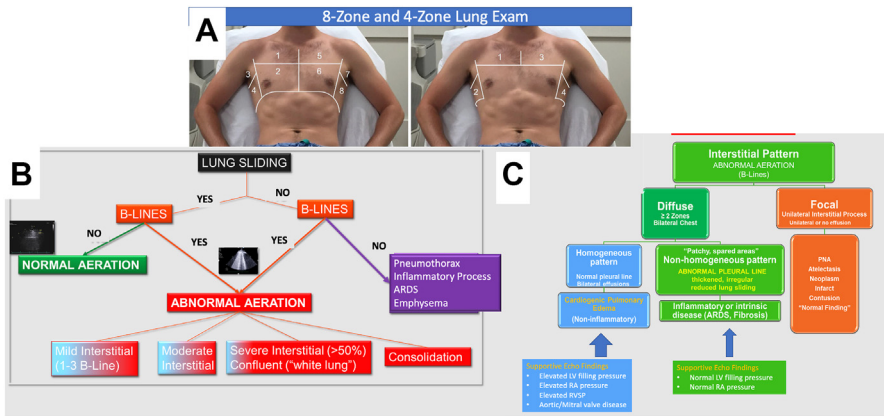

Fig. 7. Lung Ultrasound Examination (LUS) for Dyspnea (*A*). LUS can be performed using 8-zone or 4-zone protocol. (*B*) Each lung zone is first assessed for lung sliding and then the presence of B-Lines. The presence of B-Lines correlates with abnormal aeration in that lung zone. (*C*) Once the examination is completed, the pattern of B-Lines (bilateral vs unilateral), combined with additional LUS findings (pleural abnormalities) and echocardiography, guides the diagnosis of respiratory pathology. ARDS, acute respiratory distress syndrome; LV, left ventricle; RA, right atrial; RVSP, right ventricular systolic pressure. (*Courtesy of* Brandon M. Wiley, MD; Los Angeles, CA.)

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Abdominal Ultrasonography

The abdominal component of CCUS is a focused assessment that is directed toward the identification of intra-abdominal free fluid and potential etiologies of renal failure. The Focused Assessment with Sonography in Trauma (FAST) examination is a rapid and highly effective protocol for the detection of hemoperitoneum in the setting of blunt abdominal injury.[27] The FAST protocol can be performed using the phased array (2–4 MHz) or curvilinear (2–5 MHz) transducer to image the right upper quadrant, left upper quadrant, and suprapubic regions. The examination has a sensitivity of up to 96% and specificity of 98% for the detection of intra-abdominal fluid.[27] In the CICU, the FAST examination is particularly valuable in post-cardiac arrest patients with persistent hypotension that may be secondary to intra-abdominal bleeding due to vascular injuries caused by chest compressions during cardiopulmonary resuscitation (CPR) (**Fig. 8**). The FAST examination is also useful to identify the presence of ascites that could be the source of infection.

In the setting of acute kidney injury, focused renal and bladder ultrasound is important for the detection of hydronephrosis or bladder distension, which can signal the presence of obstructive uropathy (see **Fig. 8**).[28] Additionally, ultrasound can be

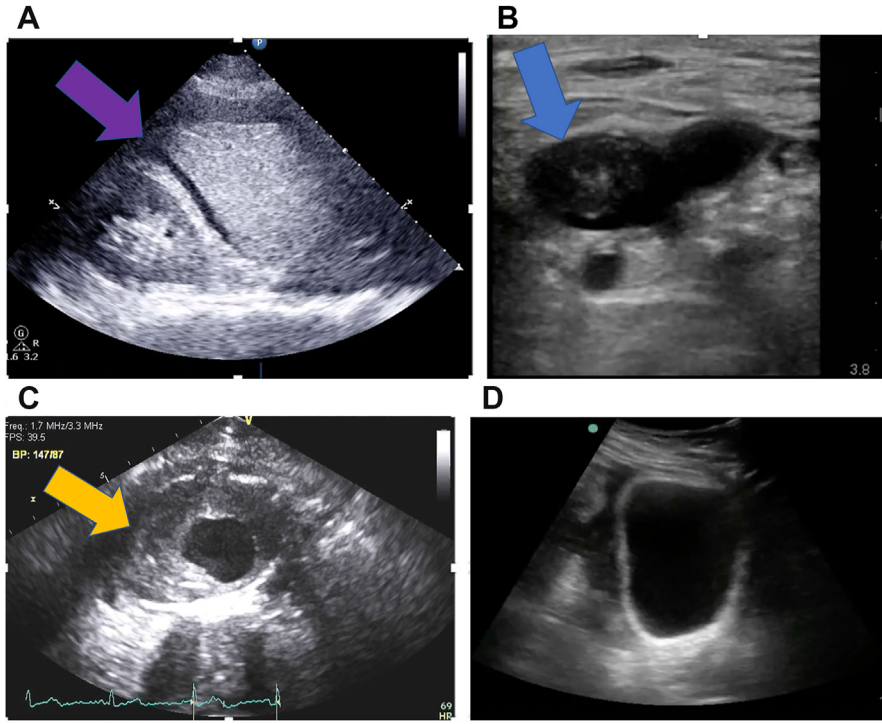

Fig. 8. Abdominal and Vascular Ultrasound Critical Findings in Cardiac Intensive Care Unit (*A*) Focused Assessment with Sonography in Trauma (FAST) examination performed after cardiopulmonary resuscitation (CPR) identifies free fluid in the abdomen, around the liver, and in the hepatorenal recess (*purple arrow*). The patient had a large bleed from a laceration of a hepatic artery caused by CPR. (*B*) Compression ultrasound demonstrates thrombus in the common femoral vein (*blue arrow*) (*C*) Abdominal ultrasound demonstrates contained rupture of abdominal aortic aneurysm. (*D*) Bladder distension from malfunctioning Foley catheter. (*Courtesy of* Brandon M. Wiley, MD; Los Angeles, CA.)

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instrumental in the management of Foley catheters through visualization of adequate bladder decompression and evaluation of balloon location.

Vascular Ultrasonography

The vascular component of CCUS is composed of abdominal aorta imaging and venous compression ultrasonography for deep vein thrombosis (DVT). The abdominal aorta can be imaged with the phased array (2–4 MHz) or curvilinear (2–5 MHz) transducer in the subcostal acoustic window. This assessment can be easily integrated into bedside echocardiography with the evaluation of the inferior vena cava and hepatic veins. It is important to rule out significant abdominal aortopathy in patients with undifferentiated epigastric pain or hypotension (see **Fig. 8**). Studies performed in the emergency room have shown that beside ultrasound has a sensitivity of up to 100% and specificity of 98% to 100% for the identification of abdominal aortic aneurysm (diameter > 3.0 cm).[29,30]

The vascular ultrasonography examination for DVT utilizes the transducer to assess venous compressibility. Normal veins are completely compressible whereas the presence of thrombus within the vein limits its compressibility (see **Fig. 8**). The examination is performed using the linear transducer (7.5–12 MHz) to compress the femoral, popliteal, peroneal, and tibial veins at 2 cm intervals.[31] The examination sensitivity (90%–96%) is maximized by starting at the inguinal ligament and extending the compression distally to the ankle.[31–33] The DVT compression ultrasonography is an important study in those patients who present with hypoxia and normal aeration pattern on lung ultrasonography.[34]

Critical Care Ultrasonography – Monitoring and Therapeutic Guidance

CCUS, particularly the Doppler echo component, provides valuable hemodynamic data that can be utilized for clinical monitoring and therapeutic guidance.

Hemodynamic Monitoring

Doppler echo provides real-time assessment of intracardiac chamber pressure and cardiocirculatory function that is comparable to the hemodynamics provided by an invasive PAC.[7] The Doppler echo LVOT VTI method for calculation of LV SV correlates well with PAC measurements and accurately tracks changes in cardiac output in critically ill patients.[35,36] In addition to providing a completely non-invasive measurement of SV, the Doppler echo method may provide a more accurate assessment of cardiac output in patients with severe tricuspid regurgitation or extremely low-flow states when compared to PAC.[37]

Fluid Management

CCUS can assess volume status and fluid tolerance and predict the hemodynamic response to fluid administration. The echocardiographic estimation of right atrial pressure can be achieved using the combination of inferior vena cava (IVC) size and collapsibility with spontaneous respiration.[38] However, the correlation of these IVC parameters with right atrial pressure is limited in those patients on invasive or non-invasive ventilation with positive end-expiratory pressure.[39] The integration of hepatic vein flow patterns into the assessment of IVC size and collapsibility has been demonstrated to significantly improve the echocardiographic evaluation of right atrial pressure in spontaneously breathing and intubated patients.[39,40] LUS can also be valuable for volume assessment since the number of bilateral B-Lines correlates with the amount of EVLW.[18,41] Although older studies have yielded mixed results for the correlation of the number of B-Lines and pulmonary capillary wedge pressure

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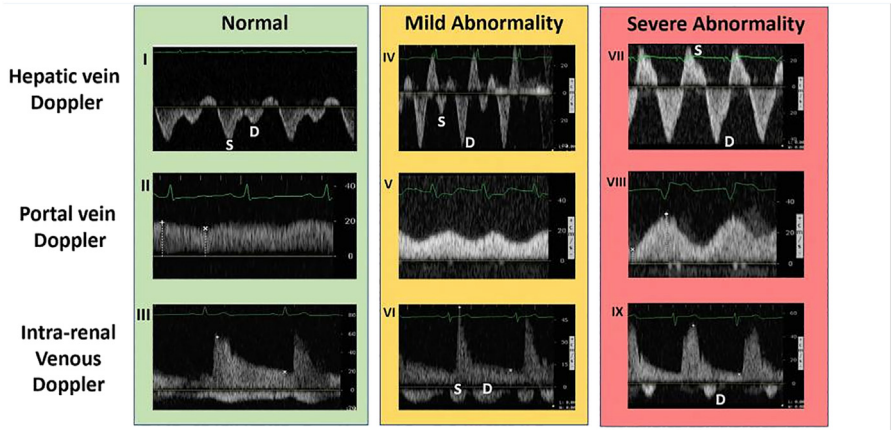
(PCWP),[41–43] more recent studies in symptomatic patients have demonstrated closer correlation with echocardiographic-derived estimates of left ventricular filling pressure and clearer thresholds for identifying elevated PCWP.[44,45] Importantly, dynamic changes in the number of B-Lines can be used to gauge the efficacy of diuretic therapy. Nobel and colleagues demonstrated that the disappearance of prehemodialysis B-Lines correlated with the volume of fluid removed.[46] Similar studies have been performed in heart failure patients with data showing that the number of B-Lines can change within 3 hours of effective diuretic therapy.[20,47] Finally, there has been a recent interest in using multiorgan ultrasound to comprehensively evaluate central venous pressure and the presence of venous congestion. The venous excess ultrasound(-VExUS) protocol incorporates IVC size and collapsibility with Doppler assessment of the portal vein, hepatic vein, renal artery, and renal vein to grade the amount of venous congestion (**Fig. 9**).[48,49] Higher grades of venous congestion by VExUS were found to be associated with an increased risk of acute kidney injury in postoperative cardiac surgery patients.[48] Although more research is required to evaluate the clinical value of VExUS, the examination appears to be most useful in those patients with a plethoric IVC where the addition of portal vein, hepatic vein, and renal vascular



	VExUS A	VExUS B	VExUS C	VExUS D	VExUS E
Grade 0	IVC < 2 cm	IVC < 2 cm	IVC < 2 cm		
Grade 1	IVC ≥ 2 cm **Normal** patterns *(All three of : I, II, III)*	IVC ≥ 2 cm **Normal** patterns *(All three of : I, II, III)*	IVC ≥ 2 cm **Normal** patterns **or mild** abnormalitie(s) *(Any combination of : I, II, III, IV, V, VI)*	**Normal** patterns *(All three of : I, II, III)*	**Normal** patterns **or mild** abnormalitie(s) *(Any combination of : I, II, III, IV, V, VI)*
Grade 2: Mild congestion	IVC > 2 cm **Mild** abnormality in **at least one** pattern *(At least one of : IV, V, VI)*	IVC > 2 cm **Mild or severe** abnormality in **at least one** pattern *(At least one of : IV, V, VI, VII, VIII, IX)*	IVC > 2 cm **Severe** abnormalities in **at least one** pattern *(At least one of : VII, VIII, IX)*	**Mild or severe** abnormalities **in at least one** pattern *(At least one of : IV, V, VI, VII, VIII, IX)*	**Severe** abnormalities **in at least one** pattern *(At least one of : VII, VIII, IX)*
Grade 3: Severe congestion	IVC > 2 cm **Severe** abnormalities **in at least one** pattern *(At least one of : VII, VIII, IX)*	IVC > 2 cm **Mild or severe** abnormalities **in multiple** patterns *(At least two of : IV, V, VI, VII, VIII, IX)*	IVC > 2 cm **Severe** abnormalities **in multiple** patterns *(At least two of : VII, VIII, IX)*	**Mild or severe** abnormalities **in multiple** patterns *(At least two of : IV, V, VI, VII, VIII, IX)*	**Severe** abnormalities **in multiple** patterns *(At least two of : VII, VIII, IX)*

Fig. 9. Venous Excess Ultrasound Protocol. This protocol grades the amount of venous congestion using Doppler ultrasound interrogation of the hepatic vein, portal vein, and renal vein. The examination provides additive information when the IVC is dilated. (*From* Beaubien-Souligny W, Rola P, Haycock K, et al. Quantifying systemic congestion with Point-Of-Care ultrasound: development of the venous excess ultrasound grading system. Ultrasound J. 2020;12(1):16. Published 2020 Apr 9.)

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flow parameters can refine the assessment of central venous congestion and identify those patients that could benefit from volume removal.[49]

The central tenet of fluid responsiveness is whether intravascular volume expansion will generate an appreciable increase in cardiac output. Ideal tests of fluid responsiveness involve dynamic changes in preload that are facilitated through heart–lung physiology or direct fluid bolus (passive leg raise or mini fluid bolus). The most common echocardiographic assessment of fluid responsiveness that leverages heart–lung interactions is the measurement of the respirophasic change of the vena cava. In mechanically ventilated patients who are passive and receiving adequate tidal volumes, respirophasic variation in the IVC diameter of 12% or superior vena cava (SVC) of 12% to 36% has been found to be reasonably predictive of fluid responsiveness.[50] Although respirophasic changes in the IVC size are commonly used in clinical practice, this technique is an unreliable predictor of fluid responsiveness in spontaneously breathing patients.[50,51] Better tests of fluid responsiveness utilize capability of Doppler echo to detect instantaneous changes in stroke volume through high-fidelity pulse-wave Doppler monitoring of the LVOT VTI. Techniques using LVOT VTI such as stroke volume variation and end-expiratory occlusion have been studied but these tests require passive mechanical ventilation and can be confounded by cardiac arrhythmias or right ventricular dysfunction.[50–52] The most straightforward application of LVOT VTI-guided fluid responsiveness is through direct preload augmentation either by an endogenous fluid bolus (passive leg raise) or via a mini "test" fluid bolus (100 mL). An increase in the LVOT VTI by greater than or equal to 10% using either of these methods is an excellent predictor of fluid responsiveness. Furthermore, these tests of direct preload augmentation are valid regardless of respiratory status (spontaneous or mechanically ventilated) or cardiac rhythm.[50,51] Finally, LUS can be incorporated into the fluid responsiveness protocol as an assessment of fluid tolerance. For example, hypotensive patients without bilateral B-Lines are more likely to be tolerant of additional fluid resuscitation, whereas patients that already have bilateral sonographic interstitial pattern (diffuse B-Lines) consistent with excessive EVLW may not tolerate additional volume loading.

Temporary Mechanical Circulatory Support

Ultrasonography plays an important role in the management of temporary mechanical circulatory support (MCS) and recent state-of-the-art reviews of the topic have been published.[53–55] In patients being evaluated for MCS, echocardiography provides rapid assessment for the presence of pathology that could be a contraindication to device placement or influence the choice of support modality. For example, prior to placement of a percutaneous left ventricular assist device (pVAD) such as Impella (AbioMed, Danvers, MA), the presence of left ventricular thrombus or critical aortic stenosis should be ruled out. TEE may be required to rule out the presence of left atrial or left atrial appendage thrombus prior to initiation of TandemHeart (TandemLife, Pittsburgh, PA). The presence of thrombus in the right heart or large intracardiac shunts may preclude placement of a right ventricular pVAD. Furthermore, the echocardiographic evaluation of biventricular function is important before moving forward with isolated univentricular support.[54] Although fluoroscopy is the standard imaging modality used for initial placement of pVAD devices, the concurrent use of echocardiography can be helpful to optimize positioning (**Fig. 10**). TEE imaging can guide the transseptal puncture and placement of the TandemHeart cannula in the left atrium and ensure the outflow cannula of right ventricular pVAD devices ProTek Duo (TandemLife, Pittsburgh, PA) and Impella RP (AbioMed, Danvers, MA) are positioned in the pulmonary artery 4 cm distal to the pulmonic valve. Once a pVAD is in place,

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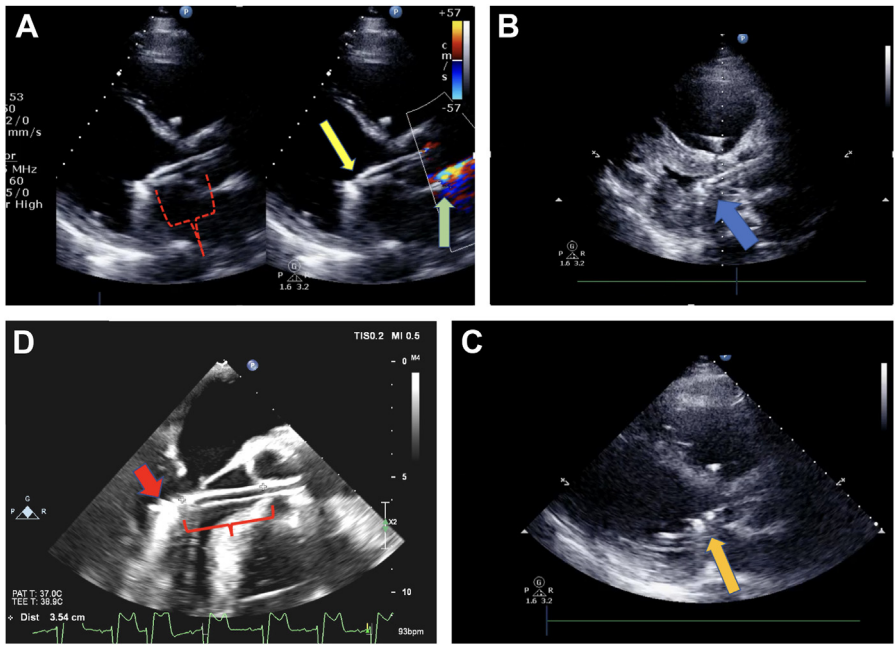

Fig. 10. Echocardiography for Percutaneous Ventricular Assist Device (pVAD) (*A*) Impella CP (AbioMed, Danvers, MA) visualized with transthoracic echo. The inlet (*yellow arrow*) at the correct depth in the left ventricle (3.5 cm, *red brackets*) and the outflow is in the ascending aorta with color artifact from flow (*green arrow*). (*B*) Left ventricular suck-down event with Impella (*blue arrow*) caused by low preload in the left ventricle. (*C*) The suck-down event is resolved and by decreasing pump speed (Impella – *orange arrow*). (*D*) Transesophageal echo of Impella CP at correct depth of 3.5 cm to inlet (*red arrow*). (*Courtesy of* Brandon M. Wiley, MD; Los Angeles, CA.)

bedside echocardiography is a fundamental diagnostic modality for device monitoring. Impella devices should be positioned with the inlet 3.5 cm (5.0 cm for the Impella 5.5) below the aortic valve annulus (see **Fig. 10**).[53,54] The Impella inlet should be directed toward the left ventricular apex to prevent interaction with the mitral valve apparatus or ventricular walls. The Impella outflow should be distal to the aortic valve in the ascending aorta and its positioning can be checked using color Doppler, which will display a characteristic turbulent artifact pattern. Prompt reimaging at the bedside is required in the setting of device alarms or any change in clinical condition (see **Fig. 10**). The development of significant hemolysis with the Impella device could signal malpositioning or interaction with the mitral valve apparatus. Any repositioning of an Impella at the bedside should be performed with concurrent echocardiographic guidance.

Echocardiography also is an important component of ECMO. TEE is typically the ideal modality since it provides visualization of guide wires, cannulas, and underlying pathology. In patients being evaluated for veno-venous ECMO (VV-ECMO), assessment of biventricular function is crucial to decide if additional circulatory support in the form of veno-arterial ECMO (VA-ECMO) is required. Although a comprehensive evaluation of biventricular function using both quantitative and qualitative parameters is recommended prior to VV-ECMO, future studies are required to determine what echocardiographic markers are most important to predict the need for escalation to

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VA-ECMO.[53,55] Once the decision for VV-ECMO has been made, TEE can guide optimization of cannula positioning. Dual-lumen cannulas can be manipulated under echocardiographic guidance to direct the outflow across the tricuspid valve and in the setting of two-site cannula configurations, the distance between the cannulas can be adjusted (~10 cm) to minimize the risk of recirculation.[56] There are currently no echocardiographic parameters that have been shown to predict successful weaning of VV-ECMO.

In patients placed on VA-ECMO support, it is important evaluate the severity of underlying aortic and mitral valve regurgitation since the increased afterload from the circuit can worsen these valvular lesions, which can inhibit adequate LV unloading and cause LV distention and pulmonary edema. Although studies regarding specific echocardiographic parameters that predict the need for LV venting are lacking, findings such as absence of aortic valve opening, LV dilation, diastolic mitral regurgitation, and spontaneous echo contrast in the left ventricle or left atrium have been suggested as key factors.[57] In cases of suspected inadequate LV unloading, LUS can monitor for the development of worsening pulmonary edema. If an LV venting strategy is pursued, TEE can guide placement of the device (Impella, intra-aortic balloon pump, drainage catheter).[55] Echocardiography is also utilized for the monitoring of ventricular recovery and prediction of successful weaning from the ECMO circuit (**Fig. 11**). Small studies have associated successful weaning from VA-ECMO with LV ejection fraction (LVEF) greater than or equal to 20 to 25%, LVOT VTI greater than or equal to 10 to 15 cm, TDI lateral mitral annular systolic velocity greater than or equal to 6 cm/s, and right ventricle 3D ejection fraction greater than 25%.[58–60] However, a more recent small study found that improvement in TDI of the lateral mitral annular e' velocity and lateral tricuspid annular systolic velocity during weaning of the ECMO circuit outperformed LVEF, mitral annular systolic velocity, and LVOT VTI for prediction of successful weaning.[61] Given the limited existing data, more prospective studies are required to determine the optimal echocardiographic predictors of successful weaning from VA-ECMO.

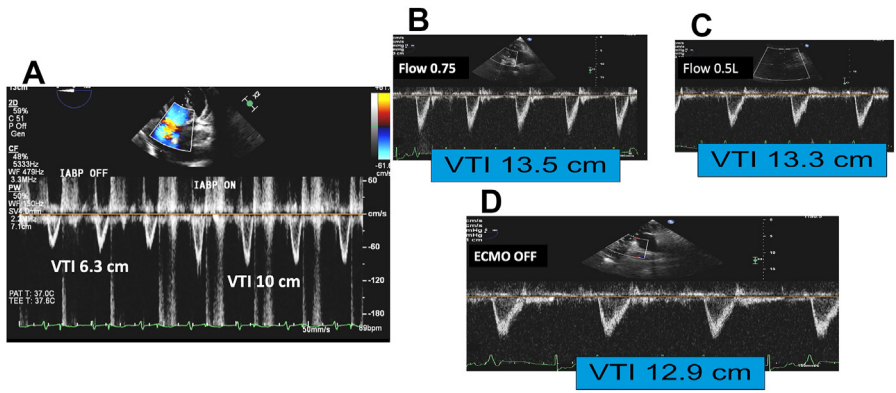

Fig. 11. Doppler Echo Hemodynamic Monitoring of Mechanical Circulatory Support (*A*). The spectral Doppler demonstrates a near doubling of the left ventricular outflow tract velocity-time Integral (LVOT VTI) with initiation of the intra-aortic balloon pump (IABP). This change in LVOT VTI equates to a doubling of left ventricular stroke volume with IABP support. (*B–D*) These images demonstrate the monitoring of LVOT VTI during wean of veno-arterial extracorporeal membrane oxygenation (VA-ECMO). The LVOT VTI is stable during the wean at very low ECMO flow, which predicted successful wean (LVOT VTI unchanged with ECMO off). (*Courtesy of* Brandon M. Wiley, MD; Los Angeles, CA.)

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Cardiopulmonary Resuscitation

Clinical ultrasound has been shown to aid in the identification of reversible causes of cardiac arrest and detect cardiac motion in the setting of pulseless electrical activity.[62] However, current guidelines recommend that ultrasound during CPR is performed by experienced sonographers to avoid prolonged pauses in chest compressions and therefore specific protocols have been developed to optimize the integration of diagnostic ultrasound into Advanced Cardiac Life Support practice.[62,63] Additionally, although the absence of cardiac motion (cardiac standstill) has been associated with failure to achieve return of spontaneous circulation, current advanced life support guidelines recommend against using cardiac ultrasound for prognostication due to a paucity of strong clinical data.[64]

CRITICAL CARE ULTRASOUND – PROGNOSTICATION

Beyond the utility of CCUS diagnosis and clinical monitoring, there is also prognostic value for patient outcomes using Doppler echo-derived hemodynamics and lung ultrasound.

Doppler Echo Hemodynamics

Doppler echo hemodynamics provides important prognostic information in the CICU. A study of admission echocardiograms in 6957 CICU patients found that an LVOT VTI less than 16 cm was the strongest predictor of in-hospital mortality regardless of admission diagnosis.[65] As a direct echocardiographic assessment of LV forward flow and stroke volume, the LVOT VTI outperformed the LVEF in prognostic value. In this study, the mitral annular E/e' ratio, a Doppler echo parameter of LV diastolic function and LV filling pressure, was also prognostically important with elevated E/e' values associated with increased in-hospital mortality.[65] An elevated mitral annular E/e' ratio has also been shown to predict mortality in patients presenting with acute myocardial infarction and in cases of out-of-hospital cardiac arrest.[66–69] The combination of E/e' ratio and LVOT VTI has been shown to risk stratify CICU patients in a manner analogous to the classic Diamond–Forrester profiles. The highest in-hospital and at 1-year mortality rates corresponded to patients with the combination of elevated LV filling pressure (E/'e > 14) and reduced LV stroke volume (LVOT VTI < 16 cm).[70] The combination of E/e' greater than 15 and echocardiographic stroke volume index less than 35 mL/m^2 (calculated via LVOT VTI) was also found to have the strongest association with in-hospital mortality in 5453 CICU patients stratified by the Society for Cardiovascular Angiography and Intervention (SCAI) shock stages.[71] Mitral annular E/e' can also be used to calculate an echocardiographic assessment of left ventricular stroke work index with lower values corresponding to higher in-hospital and 1-year mortality for all-comers to the CICU.[72]

In the landmark Should We Emergently Revascularize Occluded Coronaries for Cardiogenic Shock trial, cardiac power output (CPO) was found to have the strongest correlation with in-hospital mortality.[73] Subsequent studies assessing echocardiographic measurements of CPO had similar findings, with a CPO cutoff less than 0.6 W associated with significantly greater odds of adjusted in-hospital mortality.[71,74] When this cutoff was combined with a lactate of greater than 4 mmol/L, a greater than 50% in-hospital mortality was noted. The same CPO cut-off was also independently associated with a 34% increase in mortality at 1-year, compared to patients with higher and more preserved CPO values.[74]

Prognostically important Doppler hemodynamic variables are not limited to the left ventricle. Right ventricular-pulmonary artery (RV-PA) coupling can be quantified by

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Doppler echocardiography parameters, utilizing tricuspid annular planar systolic excursion (TAPSE) or tricuspid annular systolic velocity (TASV) as surrogates for RV function, and the combination of right atrial pressure estimates with tricuspid regurgitation velocity to estimate RV systolic pressure (RVSP).[75] In a retrospective analysis of 4259 CICU patients, impaired RV-PA coupling defined as low TASV/RVSP ratio at time of admission, regardless of diagnosis, was independently prognostic of in-hospital and 1-year mortality.[76] Additionally in the CICU, elevated RVSP measured by echocardiography at admission was shown to be independently associated with increased risk of in-hospital mortality and mortality at 1 year, regardless of admission diagnosis. This was particularly pronounced for the subgroup of patients with an RVSP greater than 50 mm Hg or with concomitant RV dysfunction.[77] From the standpoint of RV function as assessed by TAPSE, the cutoff of 14 mm for stratifying prognosis has also been noted in other patient populations, including ST-segment elevation myocardial infarction with or without cardiogenic shock, and all-comers admitted for decompensated heart failure requiring diuresis.[78,79]

Speckle-Tracking Echocardiography

Speckle-tracking echocardiography is a semi-automated technique that uses acoustic markers within the 2D-echo image to analyze myocardial mechanics. The most used speckle-tracking parameter is global longitudinal strain (GLS), which is highly sensitive metric of ventricular systolic function that can detect the presence of subclinical dysfunction. Although some studies have found abnormal GLS of the left and right ventricle to be independently predictive of mortality in sepsis and septic shock, the data remain mixed and additional research is needed to better define the value of this technique.[80–82] Recent studies have also suggested an association with subclinical ventricular dysfunction (abnormal GLS) and mortality in coronavirus disease 2019.[83,84]

Lung Ultrasound

B-Lines as a marker of pulmonary vascular congestion have significant prognostic value. In patients presenting with acute decompensated heart failure, increasing number of B-Lines at admission and discharge were associated with adverse in-hospital events, readmission, and death.[20,85] In patients presenting with acute myocardial infarction, increasing B-Lines at the time of admission also correlated with increased risk of in-hospital mortality and improved the precision of other prognostic schema, such as the Killip classification and SCAI shock staging.[86,87]

CRITICAL CARE ULTRASOUND – SUMMARY AND FUTURE DIRECTIONS

Although echocardiography remains the foundation of the ultrasound evaluation in the CICU, a paradigm of CCUS has developed through the integration of focused lung, abdominal, and vascular ultrasonography. The practice of CCUS can be further advanced through prospective studies assessing the clinical benefit of diagnostic multiorgan system ultrasonography. In addition, although Doppler echo-derived hemodynamics correlates well with invasive parameters, most studies addressing prognostic echocardiographic parameters for risk-stratification and short-term mortality have been retrospective cohort studies and prospective validation in multicenter studies is required to delineate the utility of these identified parameters. Finally, the most important future direction of CCUS involves the integration of artificial intelligence (AI) into clinical practice. AI is rapidly being incorporated into echocardiography with automated measurements and disease detection algorithms.[88] Additionally, deep

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learning models are being used to train novices to perform diagnostic echocardiogram and to identify the etiology of respiratory failure using LUS.[89,90] The advancement of AI technology and its incorporation into CCUS may provide for automated detection of critical findings (pericardial effusion, LV dysfunction), hemodynamic measurements (LVOT VTI, right atrial pressure estimates), and underlying pathology (pneumonia, pulmonary edema).

CLINICS CARE POINTS

- Left ventricular stroke volume and cardiac output assessed using echocardiography can be performed quickly in critically ill patients and correlates well with invasive measurements.
- It is important to average multiple measurements of the left ventricular outflow tract velocity-time-integral (LVOT VTI) when assessing the stroke volume in patients with irregular heart rhythms such as atrial fibrillation.
- The size and collapse of the inferior vena cava does not correlate well in right atrial pressure in patients receiving positive end-expiratory pressure (PEEP) either through non-invasive ventilation or invasive mechanical ventilation. The definitive measurement of right atrial pressure in the setting of PEEP is through invasive assessment.
- B-Lines on lung ultrasound signify the presence of abnormal aeration of the lung and are not specific for pulmonary edema. The interpretation of etiology of B-Lines requires evaluation of the pattern of these ultrasound findings (unilateral vs bilateral, diffuse versus patchy) as well as integration of the clinical physician exam and other ultrasound findings.
- In hemodynamically unstable post-cardiac surgical patients or trauma patients with suboptimal transthoracic acoustic windows, it is important to move quickly to transesophageal echocardiography to define cardiac hemodynamics and rule out the presence of mechanical complications or the presence of a pericardial effusion.

DISCLOSURE

The authors have nothing to disclose.

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